

# One– vs. Two–Shock Heliosphere: Constraining Models with GHRS $L\alpha$ Spectra toward $\alpha$ Cen

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## ABSTRACT

Redshifted  $L\alpha$  absorption toward  $\alpha$  Cen has been interpreted by Linsky & Wood (1996) and Frisch *et al.* (1996) as evidence for decelerated interstellar hydrogen piled up on the upstream side of the heliosphere. We utilize newly developed two-dimensional multi-fluid models of the solar wind interaction with the ISM to corroborate this interpretation by synthesizing the  $L\alpha$  absorption profile predicted for this “hydrogen wall”. Both subsonic and supersonic inflow into the heliosphere are considered, corresponding to one-shock and two-shock global morphologies, respectively. It is found that these two extremes give observably different redward absorption characteristics in the  $L\alpha$  profiles, and our preliminary conclusion is that the  $L\alpha$  profiles seen toward  $\alpha$  Cen favor a barely subsonic model (Mach number 0.9). For such a model to hold, additional interstellar pressure terms, such as cosmic ray or magnetic pressures, must contribute. To make this conclusion more certain, an extended model-parameter survey is required, coupled with  $L\alpha$  data along other lines of sight.

*subject headings: interplanetary medium – ISM: general – shocks*

## 1. Introduction

The interaction of interstellar neutral particles with ambient plasma near the boundary between heliospheric and interstellar material (the heliopause) is of fundamental importance to the structure of the heliosphere. The length scale of the coupling between the neutral and plasma populations is on the order of 100 AU, which is much larger than the characteristic plasma scales in the magnetic barrier at the heliopause. This allows the neutrals to decouple from the plasma, penetrate the barrier, and alter the heliospheric environment. Indeed, excluding planetary atmospheres,  $\sim 98\%$  of the diffuse gas in the heliosphere originates in the surrounding interstellar cloud (SIC).

The shock structure in the outer heliosphere consists of the termination shock (TS) where the solar wind goes from supersonic to subsonic, the heliopause (HP), which is the stagnation surface between deflecting interstellar ions and hot subsonic solar wind plasma, and the possible bow shock (BS) where the interstellar flow goes from supersonic to subsonic. Heliospheric models with both a termination shock and bow shock are referred to as “two-shock” models, while models where the interstellar flow is subsonic are commonly referred to as “one-shock” models (no bow shock). The difference lies in the strength of the restoring forces that respond to plasma compression in the SIC.

The characteristic properties of the SIC have been determined from a combination of observations of nearby stars, observations of pick-up ions in the solar system, and direct observations of interstellar neutral helium at 5 au (Piskunov *et al.* 1997; Witte *et al.* 1993). The general cloud properties include neutral hydrogen density  $n_{tot} \sim 0.2 \text{ cm}^{-3}$ , electron density  $n_e = 0.1\text{--}0.3 \text{ cm}^{-3}$ , and temperature  $T \cong 7000 \text{ K}$ , which gives a plasma thermal sound speed of  $v_{th} \cong 14 \text{ km/s}$ . In the absence of cosmic-ray pressure, a bow shock forms around the heliosphere when the relative Sun-SIC velocity is larger than the magnetosonic velocity, which perpendicular to the magnetic field is  $v_{ms} = (v_{th}^2 + v_a^2)^{1/2}$ ,

where  $v_a \sim 2.18B(\mu\text{G})/\sqrt{n_e}$  km/s is the Alfvén speed. For characteristic estimates  $n_e \sim 0.1$  cm<sup>-3</sup> and  $T \sim 7,000$  K, and adopting  $B \sim 1.6\mu\text{G}$  (Frisch 1991), the plasma thermal sound speed is 14 km/s and the Alfvén speed is 11 km/s, so the combined signal propagation speed is  $\sim 17$  km/s. Since the SIC has an observed velocity vector of  $-26$  km/s relative to the Sun (arriving from the direction  $l=0^\circ$ ,  $b=+16^\circ$ ; Witte et al. 1993; Bertin *et al.* 1993), this would imply that the solar system has a Mach 1.5 bow shock. For this reason, two-shock models of the heliosphere (Baranov & Malama 1993, 1995; Pauls et al. 1995, Pauls & Zank 1996a,b; Zank et al. 1996a,b; Williams et al. 1996a,b), have received the most attention to date.

On the other hand, elementary estimates of the local interstellar medium (LISM) parameters that include cosmic-ray pressure suggest that the interstellar flow may be subsonic (Zank *et al.* 1996a,b). Also, the possibility that the bow shock may be smoothed out by ion-neutral effects in the presence of the interstellar magnetic field, giving rise to an effective one-shock model, has been suggested (Mullan & Arge 1995). Independent of these considerations, when interstellar neutrals are included self-consistently, the neutral flow across the heliopause region is always seen to be compressed, heated, and decelerated in the nose region upstream of the heliopause. However, since the detailed structure of the compressed region, referred to as the “hydrogen wall”, varies considerably between one- and two-shock models, the availability of sensitive diagnostics of this region would offer a powerful probe of the global structure of the heliosphere.

One potential diagnostic would be the direct observations of such a wall in the heavily saturated  $\text{L}\alpha$  line. As will be shown in this paper, this pileup is detectable in directions where the decelerated hydrogen is redshifted out of the shadow of the interstellar absorption, if the interstellar column density is low enough. Linsky & Wood (1996, hereafter LW) and Frisch *et al.* (1996) attributed the redshifted excess absorption in *HST*  $\text{L}\alpha$  observations

toward  $\alpha$  Cen (earlier seen by *Copernicus* and *IUE*, Landsman *et al.* 1984) to the solar hydrogen wall. Having galactic coordinates  $l = 316^\circ$  and  $b = -1^\circ$ ,  $\alpha$  Cen lies  $52^\circ$  away from the upstream flow into the heliosphere. This is close enough to the upwind direction to sample the hydrogen wall, which should not be seen in downstream observations. If the excess absorption is indeed of heliospheric origin, this would provide a direct signature of the presence of the hydrogen wall and a quantitative probe of its attributes.

In this paper, we present a direct comparison between the  $\alpha$  Cen  $L\alpha$  data and the  $L\alpha$  absorption predicted by detailed heliospheric models that account for partially coupled plasma/neutral hydrodynamics. Our purpose is to test the following two key hypotheses, both of which will be supported by our results. (i) Synthetic  $L\alpha$  absorption profiles generated from 2D models of the solar-wind/LISM interaction provide strong theoretical support that the observed redshifted absorption is heliospheric. (ii) Quantifiably distinct  $L\alpha$  absorption profiles arise from one- and two-shock models, and a resolution of  $10^5$  (such as for the GHRS echelles) is sufficient to differentiate between them.

In §2 of this paper we summarize the observational evidence for the heliospheric  $H^{\circ}$  pile-up toward  $\alpha$  Cen. The  $L\alpha$  absorption from a homogeneous hydrogen wall is considered in §3. In §4, we introduce a more realistic hydrogen wall, using multi-fluid heliosphere models developed by Pauls et al. (1995, 1996a,b), Zank et al. (1996a,b), and Williams et al. (1996a,b). These model predictions are compared with the  $\alpha$  Cen spectra in §5. In §6, we discuss the value of future observations along other sightlines, and for each direction we predict the LISM column depth which would completely obscure the heliospheric absorption signature for each of the models. In §7 we discuss how heliospheric models can be used to reduce uncertainties in observations of the upstream LISM D/H ratio. Our overall conclusions are summarized in §8. Appendix A shows that the conductive interface models by Slavin (1989) cannot reproduce the observations toward  $\alpha$  Cen, and in Appendix B we

discuss our theoretical models in more detail.

## 2. Signature of the Heliosphere in $\alpha$ Cen Spectrum

Landsman et al. (1984) first discovered that the centroid of the foreground absorption seen in H $^{\circ}$  L $\alpha$  spectra of the nearby solar twin  $\alpha$  Cen A exhibited an unexplained  $8 \pm 2$  km/s redshift with respect to the D $^{\circ}$  L $\alpha$  absorption feature. This conclusion was based on two *Copernicus* and eight *IUE* spectra acquired over a period of four years. They interpreted the velocity offset as evidence for two clouds in this sightline. LW repeated the observation with the greatly improved spectral resolution of the GHRs Echelle A, and found evidence for at least two separate structures, one with the expected LISM properties and the other more redshifted component with a possible hydrogen pile-up at our heliosphere. They also explored the possibility that a third, *blueshifted* component associated with the asterosphere of  $\alpha$  Cen might be present in the data. Other interpretations may be possible, but the overall redshift of the H absorption could not be created by any known interstellar cloud in the line of sight (Lallement *et al.* 1995). The possible presence of a heated conductive interface along the line of sight is also an unlikely interpretation, as argued in Appendix A. Thus, the goal here is to critically explore the interpretation that this redshifted feature is due to decelerated neutral hydrogen at the heliosphere, using detailed models which include recent advances in heliospheric physics.

We first show the LW observations in Figure 1, and describe our approach for isolating the possible heliospheric signature. The solid curves in Figure 1 are the observed profiles for  $\alpha$  Cen A (Figure 1a) and  $\alpha$  Cen B (Figure 1b). The wavelength scale in both figures is relative to L $\alpha$  line center in the heliocentric rest frame. Note that the conversion to a velocity scale is given by  $0.1 \text{ \AA} = 25 \text{ km/s}$ . The chromospheric emission lines show two

obvious foreground absorption features, a wide and saturated feature due primarily to absorption by interstellar neutral H, and a narrow unsaturated feature due to absorption by interstellar deuterium.

In order to determine the amount of absorption, the intrinsic stellar emission profile must be specified. We start with assumed intrinsic profiles shown as dashed lines in Figure 1. The true profiles are not known for either star, although  $\alpha$  Cen A has the same spectral type (G2 V) as the Sun. The secondary  $\alpha$  Cen B is also a dwarf, though is substantially cooler (K1 V). Our approach is to take the intrinsic solar  $\text{L}\alpha$  profile (Brekke *et al.* 1991) and rescale it linearly in both wavelength and intensity to fit the wings of the observed profiles. For the conclusions of our paper, an accurate representation of the intrinsic stellar profile is not required, since the features in which we are ultimately interested are quite sharp, representing absorption that varies dramatically over a frequency interval that is comparable to the Doppler width in the stellar  $\text{L}\alpha$ -forming region. Any scheme for generating plausible profiles that vary only gradually over such a narrow interval would be acceptable.

The next step is to model the interstellar attenuation, so that any residual absorption isolates the potential heliospheric signal. The dotted curves in Figure 1 give the attenuation of the stellar emission by an interstellar cloud with neutral column depth  $N_H = 4.5 \times 10^{17} \text{ cm}^{-2}$ , velocity  $v = -18 \text{ km/s}$ , and Doppler broadening  $b = 9.3 \text{ km/s}$ . These values are taken from the LW paper. Here  $N_H$  was fixed by scaling to the deuterium column density  $N_D$  assuming  $\text{D/H} = 1.6 \times 10^{-5}$ . This D/H value is supported by downstream observations (away from the heliospheric hydrogen wall) toward Capella (Linsky *et al.* 1993), and is consistent with similar data in all directions (Wood *et al.* 1996). (In §6, we discuss the effects of modifying the assumed D/H ratio.)

Figure 1 shows clearly that additional absorption both redward and blueward of the

main interstellar feature is required to complete the fit. Also, the additional absorption must be applied preferentially to the redward side, so even if we arbitrarily increased the assumed ratio of H to D, a fit could not be achieved. LW and Frisch *et al.* (1996) interpreted the redshifted absorption as a distinct component associated with the heliosphere. Frisch *et al.* (1996) used early models by Zank *et al.* (1996b) to model the heliospheric feature; our goal here is to apply recent models that include an advanced treatment of neutral/plasma coupling in the heliosphere for our calculation of the expected  $L\alpha$  absorption.

### 3. Basic Diagnostics of a Hydrogen Wall

$L\alpha$  absorption from neutral hydrogen that has been heated and decelerated in the region upstream of the heliopause provides a useful probe of the physics in the heliospheric boundary layers. Prior to calculating the absorption signature from detailed models, however, it is useful to explore in a general way the effect of a neutral interstellar/heliosphere interface on incident  $L\alpha$  profiles. To do this, we consider the absorption for constant values of the broadening speed  $b_{hw}$  and velocity  $v_{hw}$  over a specified column density  $N_{hw}$ . Since the column density of the hydrogen wall is expected to be  $< 10^{15} \text{ cm}^{-2}$  (Zank *et al.* 1996), the extended Lorentz wings of heliospheric hydrogen cannot accumulate any appreciable opacity, so we restrict our analysis to the Doppler core.

The optical depth of the  $H^o$  pile-up is then

$$\tau_{hw}(\lambda) = \frac{7.5 \times 10^{-13}}{b_{hw}} N_{hw} e^{-(247\lambda - v_{hw})^2/b_{hw}^2}, \quad (1)$$

where  $v_{hw}$  and  $b_{hw}$  are in km/s (and negative  $v_{hw}$  corresponds to motion toward the Sun), and  $\lambda$  is in Å from line center in the heliocentric rest frame. The narrow absorption domain of interest in Figure 1 appears in the vicinity of +0.1 Å, corresponding to a sub-population



moving at +25 km/s away from the Sun. LW found they could achieve a reasonable fit to the profile in this domain using  $N_{hw} = 3 \times 10^{14} \text{ cm}^{-2}$ ,  $b_{hw} = 22 \text{ km/s}$ , and  $v_{hw} = -8 \text{ km/s}$ , where we have averaged their results for  $\alpha \text{ Cen A}$  and  $\text{B}$  when there were slight differences. Using these parameters, eq. (1) yields  $\tau_{hw} = 1.12$  at  $\lambda = +0.1$ . Thus, a simple constraint we can impose is that any heliospheric model invoked to explain this absorption feature must yield an optical depth of roughly unity at  $\lambda = +0.1$  in the heliocentric frame.

Since the column depth of the hydrogen wall is three orders of magnitude smaller than the column depth in the LISM toward  $\alpha \text{ Cen}$ , it may be surprising at first glance that the heliospheric optical depth at +0.1 Å is of the same order as the LISM optical depth at that wavelength. The key difference is that the neutral flow into the hydrogen wall is heated and decelerated (and/or deflected), which both broadens and redshifts the heliospheric component away from the -0.07 Å centroid of the LISM absorption and toward the +0.1 Å wavelength of interest.

To compare the relative importance of the temperature increase and the velocity shift in allowing the hydrogen wall to be visible, we find simply from eq. (1) that decelerating the projected velocity of the hydrogen wall along the  $\alpha \text{ Cen}$  sightline by an additional 1 km/s (from -8 km/s to -7 km/s) has the same effect as increasing the temperature by 2300 K (if  $b_{hw}$  is purely thermal, so that  $T_{hw} = 61b_{hw}^2$ ). Each would increase the optical depth by 15%. Since the LW  $v_{hw}$  is redshifted by 10 km/s relative to the LISM, and heated by about 24,000 K, crudely extrapolating the above analysis suggests that each of these effects contributes about equally toward making the hydrogen wall visible. However, the nonlinear response to temperature rapidly becomes important as the temperature falls, and eq. (1) indicates that  $\tau(0.1)$  falls by a factor of 5 if  $b_{hw}$  is reduced to 16 km/s, corresponding to  $T_{hw} \cong 16,000 \text{ K}$ . For this reason, in the numerical results below, the temperature is the parameter that shows the most significant variations. The velocity and column depth

structure also vary from model to model, however, and they too affect the profiles.

#### 4. Model Characteristics

Although heuristic models illustrate the overall hydrogen wall characteristics, the value of  $L\alpha$  diagnostics is that they are sensitive to the details of the heliospheric physics. In this paper we apply such models, which include recent advances in heliospheric simulation. The LISM inflow parameters in the three models are summarized in Table 1, and the details of the simulations are given in the above references. Models 1 and 2 are drawn from previous work (Pauls *et al.* 1995; Zank *et al.* 1996a,b), and model 3 represents new results derived specifically to better fit the GHRs data. For reference, we summarize the three models in Appendix B.

The hydrogen wall attributes depend on the assumed values of the LISM inflow parameters (see Table 1), which include the density of electrons ( $n_e$ ) and neutrals ( $n_H$ ) in the surrounding LISM, their temperature  $T$  (assumed equal), the speed ( $v$ ) of heliospheric motion relative to the LISM, and the ratio of  $v$  to the propagation speed of pressure disturbances in the plasma. This last parameter, the Mach number, is critical for determining the qualitative hydrodynamic response. It depends on the pressure, which here is defined as the thermal proton pressure times a correction factor  $\alpha$ ,

$$P = \alpha n_p k T_p, \tag{2}$$

where  $n_p$  is the proton density and  $T_p$  is the proton temperature.

The parameter  $\alpha$  (see Table 1) accounts not only for the electron pressure, but also for any added contribution from cosmic ray pressure or a perpendicular magnetic field. Thus for a pure hydrogen plasma with  $n_e = n_p$  and  $T_e = T_p$ , we have  $\alpha = 2$  as in model 1.

The higher  $\alpha$  values in models 2 and 3 imply additional contributions which increase the effective sound speed, given by

$$v_s = \sqrt{\gamma \alpha k T_p / m_p} = 11.7 \sqrt{\frac{\alpha T_p}{10^4}} \quad (3)$$

measured in km/s, where  $\gamma = 5/3$  is the adiabatic index and  $m_p$  is the proton mass. The increase in mean atomic mass from helium and other species is not included, but would simply alter  $\alpha$  accordingly.

The plasma Mach number governs the qualitative behavior of the heliosheath, and is thus a key discriminant when considering the  $L\alpha$  absorption. The higher the Mach number, the greater the visible absorption, due to the elevation of the temperature of the wall (cf. §3). The heating of the plasma occurs not only due to adiabatic compression, but also to charge exchange, which passes an electron from a neutral to a proton. This important process transports energy across the magnetic boundary between heliospheric and LISM plasma, because neutrals are not deflected by the magnetic field. They may therefore cross the boundary freely and charge-exchange on the other side, creating a neutral population with the attributes of the plasma. They may then return across the boundary and charge-exchange again, and the net effect is to couple the partially ionized plasmas across the magnetic barrier, as discussed in more detail in Appendix B.

This process is especially significant for the heliosphere because the termination shock strongly heats the solar-wind plasma, and charge-exchange with inflowing neutrals allows the transfer of this heat into the plasma in the hydrogen wall region, which in turn is transferred to the neutrals in the hydrogen wall via further charge exchanges. The overall effect is to siphon off some of the solar-wind kinetic energy flux and to deposit it as thermal energy, via three separate charge exchange events, into the hydrogen wall. Higher inflow Mach numbers allow this process to occur more efficiently, by allowing a greater penetration of interstellar neutrals into the termination-shock-heated plasma of solar-wind origin. There

is also more adiabatic heating for high Mach numbers, all of which serves to elevate the characteristic  $T_{hw}$ .

As argued above, elevated temperature in the hydrogen wall is a key factor in allowing the heliospheric  $L\alpha$  absorption to be visible beyond the wavelengths saturated by LISM absorption. The other important factors were the deceleration (or deflection) of the flow, and the column depth of the wall. Thus for a simple comparison, in Table 2 we estimate a representative temperature  $T_{hw}$ , line-of-sight speed  $v_{hw}$ , and column depth  $N_{hw}$  of the hydrogen wall along the  $52^\circ$  sightline for each of the models in Table 1, and give for comparison the LW empirical fit.

Owing to gradients, the definition of characteristic values is somewhat arbitrary. We chose the values in Table 2 by averaging the parameters at three separate points of interest in the wall. These three points are where the temperature is maximal, where the velocity is minimal, and where the contribution to the optical depth at the key  $0.1 \text{ \AA}$  wavelength reaches its peak (see Figure 4). The value of the characteristic width  $\Delta L_{hw}$  along the  $52^\circ$  sightline is what would be required to accumulate the same optical depth at  $0.1 \text{ \AA}$  as the actual integrals over the model grid. The equivalent column depth is then  $N_{hw} = n_H \Delta L_{hw}$ . Also given to provide an overall length scale is the distance to the heliopause in the upstream direction  $D_{hp}$ , although the hydrogen wall absorption is not highly sensitive to this model-dependent parameter.

From Table 2 it is clear that higher Mach numbers yield greater heating of the hydrogen wall. If this conclusion is borne out by future parameter studies, then the sensitivity of the width of the  $L\alpha$  absorption to  $T_{hw}$  gives an observational constraint on the heliospheric Mach number. In contrast, the characteristic line-of-sight velocity  $v_{hw}$  does not vary appreciably for these models, while the equivalent column depth  $N_{hw}$  varies as a complicated function of the inflow parameters.

It can also be seen that the simulation results are substantially cooler than the heuristic LW fit, which would tend to yield less  $L\alpha$  absorption than is observed. However, this is compensated by the higher amount of deceleration and/or deflection in the simulations, i.e., a less-negative  $v_{hw}$ , which creates a greater redshift of the heliospheric absorption relative to the LISM. This hints at the lack of uniqueness of observational fits, and shows why the inclusion of heliospheric physics is essential.

Detailed depictions of the simulation results are shown in Figure 2. The figure is described in detail in Appendix B. Figures 2a and 2b give 2D plots of  $\log T$  contours, while the shading shows the density distribution, for model 1 (two-shock) and model 2 (one-shock) respectively. Figures 2c-e give line plots of the density, velocity, and temperature, respectively, along the  $\alpha$  Cen line of sight, where the dashed curve is model 1, dotted is model 2, and dot-dashed is model 3. Note the more gradual compression and deflection of the neutral flow in the one-shock models, and the reduced peak temperature of the wall, compared to the two-shock model 1.

## 5. Lyman $\alpha$ Absorption Toward $\alpha$ Cen

We are now ready to compare the detailed spectral features resulting from these various models with the actual observations, thereby learning about the possible structure of our heliosphere. The results are intended to be informative but not definitive, as a complete study over the full range of plausible plasma and neutral inflow parameters, and their application to multiple sightlines, is still needed. This computationally demanding task is in progress. Here we demonstrate that the warm  $H^o$  piled up against the heliopause cannot be ignored when interpreting Lyman  $\alpha$  data toward nearby stars in the upstream hemisphere.

The calculation of  $L\alpha$  absorption by each model involves the straightforward application

of eq. (1), using the local values at each gridpoint, and integrating over column depth along the  $\alpha$  Cen sightline ( $52^\circ$  from the upstream direction). The model grid extends to 1000 AU from the Sun, where the assumed intrinsic profile corrected for LISM absorption over a Voigt profile is incident as a boundary condition. The assumed LISM parameters, adapted from LW, are column depth  $N_H = 4.5 \times 10^{17} \text{ cm}^{-2}$ , Doppler broadening  $b = 9.3 \text{ km/s}$ , and line-of-sight velocity  $v = -18.2 \text{ km/s}$ . The values of  $b$  and  $v$  are well constrained by observations of other interstellar absorption lines toward  $\alpha$  Cen, and the effects of varying  $N_H$  are considered in §7.

Figure 3 shows the  $\text{L}\alpha$  absorption at the red edge of the LISM feature, for each of the heliospheric models listed in Table 1. This can be compared directly with the GHRs data from LW (solid curve). The synthetic spectra are convolved with the instrumental broadening of the GHRs Echelle A, which we take as a Gaussian of width  $0.008 \text{ \AA}$ , though this correction is not essential for our purposes. The Figure 3a/3b results refer to the  $\alpha$  Cen A/B data respectively. Additional absorption at the blue edge is explained below.

The key discriminant of the  $\text{H}^\circ$  pile-up is the quality of the fit at the red edge of the absorption trough, between about  $0.05$  and  $0.15 \text{ \AA}$  from heliocentric line center, where the decelerated component is visible outside of the saturated part of the interstellar line. The sloping absorption wings redward of this can be fitted with relatively minor adjustments to the assumed intrinsic stellar profile, so are not diagnostically significant.

Comparing the results of models 1–3 with the observations demonstrates the following points, all of which are robustly insensitive to the uncertainties in the intrinsic profile. (i) Heliospheric  $\text{L}\alpha$  absorption in the supersonic model (model 1) is *too strong* due to the stronger deceleration and especially the increase in temperature of the interstellar neutrals in the hydrogen wall. (ii) Heliospheric  $\text{L}\alpha$  absorption in the subsonic model with low Mach number (model 2) is *too weak*, since the more gradually diverted interstellar plasma flow

leads to less deceleration and less heating of the interstellar neutrals. (iii) The model with a barely subsonic Mach number of 0.9 (model 3) and a larger plasma density (see Table 1) does yield a favorable fit, giving compression and charge-exchange heating of the neutrals intermediate between the results of Models 1 and 2.

The consistency with GHRs data given by the parameters of model 3 should not be expected to be unique, and other combinations could also suffice. However, we strongly suspect that the incident interstellar gas flow can be neither highly supersonic nor highly subsonic, since these scenarios lead rather inevitably to  $\text{L}\alpha$  absorption that is either too strong or too weak respectively. On the other hand, it appears that a barely subsonic interstellar wind provides the proper degree of both deceleration and heating of the neutrals to fit the data. The detailed constraints on the interstellar Mach number and inflow density imposed by these data will be explored in future models.

Figure 3 also explores the cause of excess absorption on the blue edge of the saturated LISM feature, by following the LW speculation that it is due at least partially to the joint asterosphere of  $\alpha$  Cen A and B. At the level of a plausibility argument only, we assumed that the  $\alpha$  Cen asterosphere was identical to the heliosphere (i.e., models 1, 2, 3 respectively), but viewed from the appropriate angle ( $80^\circ$  from the interstellar inflow direction). This assumption is certainly not strictly warranted, but there are some similarities in the two systems, since  $\alpha$  Cen A is a solar twin and the  $\alpha$  Cen star system has a relative velocity with respect to its prevailing interstellar cloud of 22 km/s, similar to the Sun.

Note that absorption by the solar hydrogen wall is seen only at the red edge of the LISM feature, and similarly for the alpha Cen hydrogen wall at the blue edge, so that the two sides of the absorption profile are linked only by the assumed LISM attributes. The schematic  $\alpha$  Cen absorption at the blue edge for models 1, 2, and 3 is therefore also shown in Figure 3 with the same conventions as the heliospheric absorption at the red edge,

and again offers promise for an acceptable fit. This supports the view of LW that the  $\alpha$  Cen asterosphere is detected, and offers exciting possibilities for modeling the wind/LISM interaction in this system. Of course, alternative explanations are possible; for example, we show in Appendix A that a cloud interface could mimic a stellar HW for this sightline.

To understand the integrated absorption in terms of its spatial contributions from the local neutral parameters over the grid, Figure 4 shows the contribution to the optical depth at  $0.1 \text{ \AA}$  compiled over 100 AU intervals. Since the area under the curves gives the integrated optical depth at the key wavelength  $0.1 \text{ \AA}$  it provides a proxy for the overall impact of the heliosphere on the observed  $L\alpha$  profiles. The importance of  $H^o$  heating in producing observable hydrogen-wall absorption is evident since the region of greatest temperature (Figure 2e) correlates with the region of maximum contribution to the optical depth.

## 6. Heliospheric Contributions in other Sightlines

Observations along the single  $\alpha$  Cen sightline yields valuable yet limited information about the inferred Mach number of solar motion through the LISM. Data from sightlines that cross the hydrogen wall along other angles would be extremely helpful for confirming the heliospheric origin of the absorption, and would provide additional constraints on the heliospheric parameters. LISM column depths substantially above  $10^{18} \text{ cm}^{-2}$  completely blanket the wavelength domain where heliospheric absorption could have appreciable opacity, therefore useful  $L\alpha$  sources are scarce. Even if some starlight penetrates at wavelengths of heliospheric absorption, the bandwidth of the signal may be too narrow to be spectrally resolved. The purpose of this section is to derive the equivalent width of the  $L\alpha$  heliospheric absorption for a given model, to determine the usefulness of a given



stellar source as a heliospheric probe, as a function of LISM column depth and instrumental resolution.

The estimate is obtained by assuming a flat stellar spectrum incident on the LISM cloud with values  $b = 9.3$  and  $v = -29 \cos \theta$  km/s (taken from LW), where  $\theta$  is the angle from the upstream direction, and the column depth  $N_H$  is treated as a variable. The stellar spectrum transmitted through the LISM, as a function of  $N_H$ , then provides the input for the calculation of the heliospheric absorption feature, for which we compute an equivalent width as a function of  $N_H$ . If the absorption is significant at any wavelength, this equivalent width gives a conservative estimate of the wavelength resolution required to clearly distinguish the feature.

The equivalent widths of the model heliospheric absorption are plotted as contours in Figure 5, as a function of  $N_H$  for each sightline, for heliospheric models 1 and 2 (shown in Figure 5a and 5b respectively). Model 3 is intermediate to these results. The value of  $N_H$  that corresponds to each point on a given contour is the radial distance from the origin, measured by the scale given on the abscissa and ordinate. The angle of the sightline from the upstream direction maps directly into the angle from the abscissa, so the figure represents orientations and column depths in real space with the heliosphere at the origin. The sightlines to 36 Oph,  $\alpha$  Cen, and 31 Com would be at  $\theta = 12^\circ$ ,  $52^\circ$ , and  $72^\circ$  respectively, and are indicated. The absorption equivalent widths are measured in  $\text{\AA}$ . It is expected that observed resolution elements somewhat larger than the absorption equivalent widths in the figure may still be valuable if the signal-to-noise is high, so the contours merely provide guidelines for the preferred degree of resolution to guarantee useful diagnostics.

As an example, the resolution of the GHRS Echelle A corresponds to a Gaussian Doppler width of  $\sim 0.008 \text{ \AA}$  at  $\text{L}\alpha$ . According to Figure 5, this means that along the sightline to  $\alpha$  Cen, the heliospheric absorption can be resolved easily for LISM columns

below about  $0.7 \times 10^{18} \text{ cm}^{-2}$  and  $1.2 \times 10^{18} \text{ cm}^{-2}$  for the one-shock and two-shock models respectively. As another example, by interpolating for model 3 along the sightline to 31 Com we conclude that the heliosphere should be easily resolvable to the GHRS echelle for intervening column densities of  $N \leq 1 \times 10^{18} \text{ cm}^{-2}$ . Since the interstellar  $N_H$  column toward 31 Com is indeed around  $1 \times 10^{18} \text{ cm}^{-2}$  (Piskunov, Wood, & Linsky 1996), this illustrates the potential value of searching for heliospheric  $\text{H}^o$  absorption in high-resolution  $\text{L}\alpha$  observations of stars other than  $\alpha$  Cen. At the time of this writing, an unpublished analysis of the  $\text{L}\alpha$  absorption toward 31 Com by Dring *et al.* (1997) was unable to identify a clearly heliospheric absorption component. The quantitative constraints this imposes on the heliosphere are still being examined, but will presumably provide further evidence against strongly supersonic plasma inflow.

## 7. The D/H Ratio

Since our fundamental constraint for distinguishing between one-shock and two-shock models is the degree of excess absorption illuminated by starlight transmitted by the LISM, the LISM hydrogen column is crucial to specify. This is done by scaling to the easily inferred deuterium column, assuming that the D/H ratio takes the value that is canonical in the solar neighborhood along various other sightlines (Piskunov, Wood, & Linsky 1996), which is  $\sim 1.6 \times 10^{-5}$  (by particle, not mass).

However, if this ratio varies in the LISM, and were to be lower along the  $\alpha$  Cen sightline, then the additional LISM hydrogen absorption would require less heliospheric absorption, favoring models with an even lower Mach number. Indeed, if D/H were to be so low as a factor  $\sim 3$ , then the *one-shock* model 2 results fit both edges of the absorption extremely well, and no contribution from absorption by the  $\alpha$  Cen hydrogen wall would be

required toward the blue. Contrarily, *increasing* D/H by an order of magnitude, however implausible, would move the *two-shock* model 1 results into better agreement, and the  $\alpha$  Cen wall would then also have to contribute more strongly. This implies a connection between the assumed D/H ratio and the best-fit heliospheric model. Therefore, a variety of heliospheric models could be consistent with the data, but only if the D/H ratio can be varied by about an order of magnitude.

Since our conclusions are insensitive to small variations in D/H, it is apparent that constraint information travels more easily in the direction from knowledge about D/H into knowledge about the heliosphere, rather than the converse. With the inclusion of future observations along other lines of sight through the hydrogen wall, a suitable synthesis between the observational ramifications of both D/H and heliospheric absorption can be achieved, and confidence in a stable upstream D/H ratio may be further established. In light of the cosmological significance of D/H, this represents a rather unique interplay between heliospheric and astronomical areas of interest.

## 8. Conclusions

We have shown that high spectral resolution observations of  $L\alpha$  absorption, coupled with careful modeling of the interaction of the solar wind with the LISM, provide a useful diagnostic for remotely sampling the global structure of the heliosphere. Our conclusions are as follows.

(i) Several models (Baranov & Malama 1993; Pauls *et al.* 1995; Zank *et al.* 1996a,b) have independently corroborated the theoretical expectation that warmed interstellar neutrals should accumulate upstream of the heliopause. Our synthetic absorption profiles for three distinct heliospheric models support the detection of this hydrogen wall toward  $\alpha$

Cen by Landsman *et al.* (1984) and LW, and our barely subsonic model (Mach number 0.9) closely resembles the observations. We conclude that the hydrogen wall upstream of our heliosphere has indeed been seen. A particularly promising avenue for concretely confirming this conclusion is to combine the  $\alpha$  Cen data with archival high-resolution  $L\alpha$  spectra of 31 Com, since this would provide stereoscopic sampling of the heliosphere at angles  $52^\circ$  and  $73^\circ$  from the upstream direction.

(ii) Our model results indicate that the differences between a one- and two-shock heliosphere manifest themselves in observably distinct  $L\alpha$  absorption features, providing a powerful discriminant between these possibilities. Furthermore, application of this diagnostic exerts quantifiable constraints on the plasma and neutral environment in the inaccessible LISM. For example, the LISM parameters (temperature, density, flow speed, and fractionation) from model 3, which yield a reasonable fit to the  $L\alpha$  data, are only in good agreement with existing estimates (Frisch 1995, Gloeckler 1996) if we further stipulate that cosmic rays (or some other mechanism, such as a perpendicular magnetic field) contribute appreciably to the total interstellar pressure. The possibility that cosmic rays (e.g., Holzer 1979) or magnetic fields (e.g., Mullan & Arge 1996) could serve in this way to reduce the inflow Mach number is not unexpected, but since we have yet to undertake a comprehensive study over the full range of possible LISM inflow parameters, we cannot at present establish the uniqueness of the Mach 0.9 fit. Complementary observations, such as backscattered solar  $L\alpha$  from neutrals in the heliosphere, may provide invaluable additional constraints, since the FWHM is sensitive to the neutral heating. Thus although our results are highly suggestive, conclusive evidence of subsonic inflow awaits future work.

(iii) Models that include the charge-exchange coupling between plasma and neutrals have established the importance of a process, described in detail by Zank *et al.* (1996a) and Zank & Pauls (1996), whereby interstellar neutrals that charge exchange with very

hot shocked solar wind plasma (i.e., the “component 2” neutrals described in Appendix B) subsequently stream out into the LISM. Although of low density ( $\sim 10^{-4} \text{ cm}^{-3}$ ), these neutrals are very hot ( $\sim 10^6 \text{ K}$ ), and after a second charge-exchange process, deposit considerable heat into the plasma just outside the heliopause. This temperature increase acts to further heat the hydrogen wall via subsequent charge exchanges. The potent combination of heating and deceleration produces visible absorption in the  $\text{L}\alpha$  spectra from  $\alpha \text{ Cen}$ , and this absorption becomes more pronounced as the peak temperature increases. Models which neglect heat transport across the heliopause via charge exchange cannot produce the proper  $\text{L}\alpha$  opacity profile. Furthermore, the evidence that hydrogen-wall absorption is indeed clearly visible implies that some such heating mechanism must indeed be operating, which supports this hitherto purely theoretical picture.

(iv) Although the blueshifted absorption excess has not received close attention here, it was found that if  $\alpha \text{ Cen}$  has a relatively solar-like asterosphere, then its hydrogen wall should also be visible. This supports the suggested detection of an  $\alpha \text{ Cen}$  hydrogen wall by LW, and opens new possibilities for constraining models of the wind/LISM interaction in this nearby stellar system.

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the San Diego Supercomputer Center.

## 9. Appendix A

In this Appendix, we discuss other potential sources of excess  $L\alpha$  absorption that could mimic a heliospheric feature, and argue that, although other possibilities cannot be completely ruled out, none provide as natural and theoretically straightforward an explanation as the hydrogen wall. Since Landsman et al. (1984) concluded that the observed  $\sim +8$  km/s offset between the centroids of the  $H^o$  absorption and the  $D^o$  absorption could not be explained by uncertainties in the underlying stellar emission profile, and Linsky & Wood (1996b) ruled out uncertainties due to geocoronal emission, we must conclude that the foreground  $L\alpha$  absorption is intrinsically complex.

Since the  $H^o$   $L\alpha$  optical depth of the LISM feature lies on the saturated part of the “curve of growth”, whereas the LISM  $D^o$  and the allegedly heliospheric  $H^o$  features lie in the unsaturated linear domain, the centroid of the  $H^o$  absorption could be sufficiently shifted relative to the  $D^o$  if there exists a subset of material that is optically thick in  $H^o$  but not in  $D^o$ . Since this roughly 8 km/s offset is caused by  $H^o$  absorption near 0.1 Å (+25 km/s relative to the LISM), such small column depths could only be effective if a component exists that has a bulk velocity shift of this magnitude, or if the velocity dispersion approaches 25 km/s within a component that is itself shifted by at least 8 km/s, or some combination of the two.

Such a dispersion cannot be accomplished by overlapping pieces of observed LISM bulk flows, since the velocity difference between the main component toward  $\alpha$  Cen and the SIC (also called the LIC) clouds is only  $\sim 2.5$  km/s in this line of sight (Lallement *et al.* 1995). Therefore, we must either assume that this velocity dispersion is achieved at the atomic level via warming of a small fraction of the foreground material to temperatures of at least about 20,000 K, or postulate the existence of thin “wisps” moving at speeds around 25 km/s relative to the bulk of the LISM. There is no evidence in favor of the existence of

fast-moving wisps, so we focus on possible absorption due to the warm interfaces speculated on more physical grounds to exist (Slavin 1989) between bulk LISM clouds and the hot ISM plasma filling nearby space. Note that a cold component at the SIC velocity would not yield sufficient opacity at the wavelengths of interest to affect our conclusions.

In the model of Slavin (1989), the LISM interface is a  $\sim 0.0032$  pc layer of  $H^o$  with  $N(H^o) \sim 3.5 \times 10^{14} \text{ cm}^{-2}$ ,  $T \sim 8,000\text{--}80,000$  K, and  $v \sim 1$  km/s with respect to the cloud. We found that the theoretical velocity distribution of the heated interface neutral H yielded absorption that could be most simply fit by the sum of the two Voigt absorption features; one with and the other with  $N(H^o) \sim 1.0 \times 10^{14} \text{ cm}^{-2}$  and  $b = 28$  km/s, both moving at 0.9 km/s with respect to the underlying cloud from which it is evaporating. Our test model assumes that two such interfaces exist toward  $\alpha$  Cen, one at the edge of the main cloud toward  $\alpha$  Cen ( $-19.1$  km/s), and the other at the edge of the local (SIC) cloud (at  $-15.5$  km/s). The thermal broadening and total column depth of a warm Slavin interface for each cloud are similar to the heliopause models, and potentially difficult to distinguish. However, such interfaces do not yield sufficient velocity offset between the observed  $H^o$  and  $D^o$  features. We added two hypothetical interfaces to the LW LISM absorption without any heliospheric component, and obtain the results shown in Figure 6.

We conclude that the presence of Slavin interfaces would affect observed LISM  $L\alpha$  absorption and could complicate the interpretation of the heliospheric signal, although a heliospheric contribution would still be required to yield the observed redshift. Thus, the possibility that the heliospheric signal could be blended with warm ISM structures remains open, but there is presently no consistent evidence that this is the case.



## 10. Appendix B: Multi-fluid Heliosphere Models with Sub- or Supersonic Inflow

Two groups have developed detailed models of the interaction between the solar wind and the LISM that include the neutral hydrogen component self-consistently with the plasma. A two-dimensional (2D) Monte Carlo approach has been pioneered by Baranov and Malama (1993, 1995), while Pauls et al. (1995, 1996a,b), Zank et al. (1996a,b), and Williams et al. (1996a,b, all summarized in Zank & Pauls 1996), have instead chosen a multi-fluid approach to describe the neutral hydrogen. Both yield similar results for identical input parameters, although the simulations of the latter group have recently been extended to three dimensions (Pauls & Zank, 1996b). These latter models are also time dependent, but approach a nearly steady state. Since the details are described in the above references, we present here only an overview of the salient features of the 2D multi-fluid models we utilize for our analysis of the  $L\alpha$  absorption.

The key physical process responsible for altering the dynamics of interstellar  $H^o$  at the heliopause is the coupling to the local plasma via charge exchange, whereby the bound electron from a neutral is passed to a proton during collision without any other effect, thus swapping the neutral and proton attributes. To avoid solving the neutral Boltzmann equation directly to describe this interaction, we recognize that, to a good approximation, there exist essentially three distinct neutral H components (Holzer 1972; Hall 1993) corresponding to three physically distinct regions of origin. Neutral H atoms whose source lies beyond the heliosphere (region 1) are component 1. This “thermal” neutral component is thus interstellar in origin, although dynamical changes in the distribution result from charge exchange with interstellar plasma which has been significantly affected by the presence of the heliosphere. By contrast, neutral component 2, which is born via charge exchange in the solar-wind shock-heated heliosheath and heliotail (region 2), is

suprathermal compared to component 1, its high temperature reflecting that of the local  $10^6$  K plasma. Although of low density, component 2 can be dynamically important owing to its ability to transport heat across the heliopause. The third (“splash”) component is produced in the cold supersonic solar wind prior to reaching the termination shock (region 3), and this very tenuous component is characterized by high radially outward velocities.

Each of these three neutral components is represented by a distinct Maxwellian distribution function appropriate to the characteristics of the source distribution. This then allows us to simplify the production and loss terms corresponding to each neutral component (Ripken & Fahr 1973; Zank *et al.* 1996a; Williams *et al.* 1996a). The complete highly non-Maxwellian H distribution function is then the sum over the three components, i.e.,

$$f(\mathbf{x}, \mathbf{v}, t) = \sum_{i=1}^3 f_i(\mathbf{x}, \mathbf{v}, t). \quad (4)$$

Equation (4) allows us to express the full Boltzmann equation for the neutrals as distinct equations corresponding to each of components 1, 2 and 3, all coupled through their respective production and loss terms. From each of these component Boltzmann equations, one obtains a distinct isotropic hydrodynamic description for each of the three neutral components. Thus, our multi-fluid description comprises all three neutral fluids coupled to a hydrodynamic plasma. This rather computationally demanding time-dependent system of equations is solved in two spatial dimensions using a method developed by Pauls *et al.* (1995).

### 10.1. Two-Shock Model

Here we summarize the 2D time-dependent two-shock results obtained using the multi-fluid model. For a complete description, see Zank *et al.* (1996a) and Williams *et al.*

(1996b). Table 1 lists the parameters (model 1) used for the simulations. In Figure 2a, a 2D plot of the component 1 neutrals ( i.e., neutrals of interstellar origin) is presented. The contours denote  $\text{Log}(T)$ , the arrows show the flow direction and the shading describes the density normalized to the inflowing interstellar gas density. The hydrogen wall, where the inflowing  $\text{H}^\circ$  is compressed between the BS and HP in the upstream direction, is apparent. As described above, Figure 2c-e shows the  $\alpha$  Cen line-of-sight profiles for the density, velocity and temperature, respectively, of component 1, which is the source of the observable absorption (components 2 and 3 are too rarified to yield significant features). A detailed presentation of the plasma and component 2 and 3 neutral results is found in Zank *et al.* (1996a). The dashed curves denote the results for the two-shock case (model 1, Table 1), whose key features can be summarized as follows.

- (i) The TS is located at  $\sim 95$  AU, the HP at  $\sim 140$  AU and the BS at  $\sim 310$  AU in the upstream direction. In the sidestream and downstream directions, the TS is located at  $\sim 140$  AU and  $\sim 190$  AU respectively.
- (ii) Inflowing component 1 neutrals are decelerated substantially and filtered by charge exchange with the interstellar plasma between the BS and HP in the upstream direction, which leads to the formation of a hydrogen wall with densities up to about  $0.3 \text{ cm}^{-3}$ , column depths up to about  $10^{14} \text{ cm}^{-2}$ , and temperatures ranging from 20,000 K to 30,000 K. The pile-up in the neutral gas results from the deceleration and deflection of the neutral flow by charge exchange with the interstellar plasma, which is itself decelerated and diverted due to the presence of the heliosphere.
- (iii) Component 2, produced via charge exchange between component 1 and hot shocked solar wind plasma between the TS and HP, leaks across the HP into the cooler shocked interstellar gas and heats the plasma through a *second* charge exchange. This leads to an extended thermal foot abutting the outside edge of the HP. This heating of the

plasma by component 2 serves to broaden the region between the BS and HP, as well as to (indirectly) further heat the component 1 interstellar neutrals after *subsequent* charge exchanges. Some minor heating of the unshocked LISM also occurs upstream of the BS, thereby marginally reducing the Mach number of the incident interstellar wind.

- (iv) The temperature of component 1 neutrals once inside the heliosphere remains fairly constant in the upstream region, at  $T \sim 20,000$  K, a substantial increase over the assumed LISM temperature of 10,900 K assumed for model 1. A further increase in the component 1 temperature occurs in the downstream region.
- (v) The number density of component 1 crossing the TS is  $\sim 0.07 \text{ cm}^{-3}$ . This is approximately half the assumed incident LISM number density, an effect termed “filtration”. Between the TS and 10 AU from the Sun in the upstream region, this density varies only weakly, following a rough power law ( $\sim R^{0.25}$ , with  $R$  the heliospheric radius). In the downstream direction, component 1 densities are lower within the heliosphere and the gradient is somewhat steeper, with density increasing as  $R^{0.35}$ .
- (vi) The upstream neutral gas is decelerated from  $-26 \text{ km/s}$  in the LISM to  $-19 \text{ km/s}$  at the TS in the region of the nose. Deflection of the flow also reduces the radial velocity component at angles away from the nose.
- (vii) Zank *et al.* (1996a) point out the possibility that the HP is time dependent due to an inwardly directed ion-neutral drag term which provides an effective “gravitational” term for a stratified fluid (which then introduces the possibility of Rayleigh-Taylor-like instabilities). The time scale of 180 years and the  $\sim 3 \text{ AU}$  amplitude of the oscillation suggest that this is unlikely to be important.

## 10.2. One-Shock Model

As described in the introduction, since the SIC plasma thermal sound speed is thought to be  $\sim 14$  km/s, and the relative Sun-SIC velocity is  $\sim 26$  km/s, a two-shock heliosphere is often assumed to be necessary (Baranov *et al.* 1971). However, this neglects the effects of restoring forces due to magnetic or cosmic-ray pressure, which could enhance the effective sound speed. Unfortunately, current knowledge of either the local interstellar magnetic field or cosmic ray pressure is rudimentary. The nominal interstellar pressure contributed by cosmic rays (Ip & Axford 1985) is  $\sim 10^{-12}$  dyne  $\text{cm}^{-2}$  (which gives  $p/k \sim 7200$   $\text{cm}^{-3}$  K) with perhaps  $\sim (3 \pm 2) \times 10^{-13}$  dyne  $\text{cm}^{-2}$  contributed by cosmic rays of energy less than about 300 MeV per nucleon, which may be expected to couple to the plasma on heliospheric scales. Unfortunately, these estimates are uncertain, particularly at MeV energies. But it is important to note that a cosmic ray pressure of  $3 \times 10^{-13}$  dyne  $\text{cm}^{-2}$ , combined with the interstellar plasma thermal pressure from Table 1 ( $2 \times 10^{-13}$  dyne  $\text{cm}^{-2}$ ) yields a total pressure of  $5 \times 10^{-13}$  dyne  $\text{cm}^{-2}$  (or  $p/k \sim 3600$   $\text{cm}^{-3}$  K). This would be sufficient to increase the LISM sound speed to  $\sim 27$  km/s and force the LISM inflow to be barely subsonic. Alternatively, a magnetic field strength of  $3 \mu\text{G}$  with  $n_e = 0.05 \text{ cm}^{-3}$  gives an Alfvén speed of  $v_a = 29$  km/s, which would enhance the magnetosonic speed and also invalidate a two-shock model.

In view of the comments above, we also consider models with subsonic LISM flow, which will not have a bow shock and therefore may resemble the Parker (1963) model. For model 2, we again take  $n_e = 0.07 \text{ cm}^{-3}$ ,  $n_H = 0.14 \text{ cm}^{-3}$ , and  $T = 10,900$  K (see Table 1) for consistency with model 1, but a larger “effective” temperature is used in determining the pressure, to account for the added contribution from cosmic rays (and perhaps the magnetic field). This effective temperature is defined in terms of a parameter  $\alpha$ , as defined above. The value  $\alpha = 9.1$ , shown in Table 1, has been chosen for model 2, so the upstream Mach

number is reduced from 1.5 (as in model 1) to 0.7. No charge exchange is assumed to occur between the cosmic rays and neutrals due to the former’s low number density.

Plots of the one-shock simulations are presented in Figure 2, where (b) illustrates the 2D distribution of component 1 neutrals in the same format as used in Figure 2a. Figure 2c-e shows  $\alpha$  Cen line-of-sight profiles for the density, velocity and temperature of component 1, using dotted curves for model 2. Again, we merely summarize the main features here (and see Zank *et al.* 1996a for further details).

- (i) Although a bow shock is absent, some adiabatic compression of the incident interstellar flow is evident. This gradual compression forms a lower amplitude hydrogen wall that is more extended in the radial direction. It is also less extended in the tangential direction because of the localized nature of the adiabatic compression. The density of the wall in the upstream direction is only  $\sim 0.21 \text{ cm}^{-3}$  (though still larger than the incident LISM  $n_H=0.14 \text{ cm}^{-3}$ ). However, because it is wider, its column density is comparable to the two-shock case.
- (ii) The heliosphere is less distorted along the axis of symmetry than for the two-shock case, and is smaller due to the higher assumed LISM pressure.
- (iii) In the vicinity of the nose, the number density of component 1 flowing across the TS is  $\sim 0.06 \text{ cm}^{-3}$  with a velocity of  $\sim -20 \text{ km/s}$ , almost identical to the two-shock model.
- (iv) Since the H wall has a smaller transverse extent than the two-shock model, it is less pronounced along the sidestream sightline. This may allow the one- and two-shock models to be observably different not only upstream, but sidestream as well.
- (v) The upstream and downstream temperature characteristics of the heliospheric component 1 differ significantly between the one- and two-shock models. In the upstream direction of the one-shock model,  $\sim 2,000 \text{ K}$  of cooling for the neutrals is

predicted. A temperature asymmetry between upstream and downstream heliospheric neutrals is again present, but the downstream temperatures are markedly lower than predicted by the two shock model.

### 10.3. Intermediate Case— Barely Subsonic

To bridge the gap between models 1 and 2, we have computed a third model in which the inflow Mach number was chosen to take the intermediate value 0.9 (model 3, Table 1). In the interest of increased realism, at the cost of sacrificing consistency with models 1 and 2, we reduced the inflow temperature to the more realistic value  $T = 7,600$  K, and to compensate we increased the plasma density slightly to  $n_e = 0.1 \text{ cm}^{-3}$  so as to preserve the incident plasma heat flux. Further variations in the densities would be required to span the observably allowable domain, but this is left for future work, the present paper being restricted to the three models in Table 1.

The model 3 results for the component 1 neutrals are depicted by dot-dashed curves in Figure 2c-e. The overall structure and distribution are similar to model 2, underscoring the qualitative connection between subsonic models. The quantitative attributes of the hydrogen wall are generally intermediate to models 1 and 2, presumably owing to the intermediate value of the Mach number, which appears to be the most important single parameter.

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Table 1. Model Inflow Parameters

Model	Mach #	$n_e$ (cm <sup>-2</sup> )	$n_H$ (cm <sup>-2</sup> )	$T$ (K)	$v$ (km/s)	$\alpha$
1	1.5	0.07	0.14	10900	-26	2
2	0.7	0.07	0.14	10900	-26	9.1
3	0.9	0.1	0.14	7600	-26	7.9

Table 2. Average Properties of Model Hydrogen Walls

Model	$T_{hw}$ (K)	$v_{hw}$ (km/s)	$n_H$ (cm <sup>-3</sup> )	$\Delta L_{hw}$ (AU)	$D_{hp}$ (AU)	$N_{hw}$ (10 <sup>14</sup> cm <sup>-2</sup> )	$\tau_{0.1}$
1	23000	-4.3	0.20	210	160	6.7	2.8
2	14700	-4.3	0.19	125	140	3.8	0.6
3	16000	-4.1	0.12	325	220	6.3	1.2
LW	29500	-8	$18/L_{hw}$	$18/n_H$	–	3	1.1

### Figure Captions

**Fig. 1.** The solid curves are GHRs  $L\alpha$  profiles toward (a)  $\alpha$  Cen A and (b)  $\alpha$  Cen B, from LW. The upper dashed curve is the assumed intrinsic stellar  $L\alpha$  emission profile. The dotted curve shows the intrinsic stellar emission line after absorption by a purely LISM cloud with  $N_H = 4.5 \times 10^{17} \text{ cm}^{-2}$ ,  $b = 9.3 \text{ km s}^{-1}$ , and  $v = -18.2 \text{ km s}^{-1}$ .

**Fig. 2.** Results are depicted for the neutrals of interstellar origin from the 2D heliospheric models in Table 1. The contours denote  $\log T$ , the arrows indicate the flow direction, and the shading gives the density normalized to the inflowing interstellar gas density. The results from model 1 are in (a), and from model 2 in (b), with model 3 results being intermediate to these. The velocity, temperature, and density profiles along the  $\alpha$  Cen sightline for all three models are shown in (c-e), where the dashed curve is model 1 (supersonic), dotted is model 2 (subsonic), and dot-dashed is model 3 (barely subsonic). Negative velocities imply flow toward the Sun.

**Fig. 3.** Similar to Figure 1, except that absorption from the three heliospheric models is included. All curves from Figure 1 are reproduced as solid lines, while the dashed curve is for model 1 ( $M=1.5$ ), dotted for model 2 ( $M=0.7$ ), and dot-dashed for model 3 ( $M=0.9$ ). The profile in (a) depicts the heliospheric absorption for the  $\alpha$  Cen A profile, whereas (b) is for  $\alpha$  Cen B. The red edge of the LISM absorption feature is best fit by model 3, and note that none of the models can fit the blue edge. In order to suggest the possible importance of the  $\alpha$  Cen heliosphere in fitting the blue edge of the LISM feature, profiles (c) and (d) depict the absorption in the  $\alpha$  Cen A and B profiles (respectively) that would result if identical heliosphere models also surrounded  $\alpha$  Cen.

**Fig. 4.** Contribution functions to the optical depth in the heliospheric model at  $0.1 \text{ \AA}$  from line center (eq. 1), plotted as a function of the distance from the Sun. The axes are scaled such that the area under the curves gives the total  $\tau_{hw}(0.1)$ . The dashed curve is model

1, dotted model 2, and dot-dashed model 3, for comparison to Figure 2. Comparison with Figure 2e shows the connection to the elevated temperature structure.

**Fig. 5.** Contour plots of the equivalent width (in Å) of heliospheric  $L\alpha$  absorption as a function of LISM H I column depth ( $N_H$ ) and line of sight. We assume a LISM model with  $b = 9.3 \text{ km s}^{-1}$ ,  $v = -29 \cos \theta \text{ km/s}$ . The variable  $N_H$  is given by the distance to the origin, in the scale marked on both the abscissa and ordinate, as in a polar plot. The angle  $\theta$  in the polar plot is the angle between the nose direction and the sightline to potential stellar targets. The sightlines to 36 Oph,  $\alpha$  Cen, and 31 Com, at  $\theta = 12^\circ, 52^\circ$ , and  $72^\circ$  respectively, are indicated by dotted lines. Model 1 results (supersonic inflow) are shown in (a), and model 2 results (subsonic inflow) are in (b). Model 3 is intermediate to these. The GHRS Echelle A can easily resolve a total absorption corresponding to the  $0.008 \text{ Å}$  contour.

**Fig. 6.** A synthetic profile consisting of the LISM and two conductive interfaces (dot-dash line) as predicted by Slavin (1989). The assumed parameters are described in the text. The dashed curve shows the absorption by the LISM alone. The total amount of absorption seen is nearly in agreement with the observations, except for a telling lack of appropriate overall redshift and an excess of highly broadened (high  $T$ ) absorption.



























